Photon-axion conversion as a mechanism for supernova dimming: Limits from CMB spectral distortion

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Axion-photon conversion induced by intergalactic magnetic fields has been proposed as an explanation for the dimming of distant supernovae of type Ia (SNe Ia) without cosmic acceleration. The effect depends on the intergalactic electron density n_e as well as the B-field strength and domain size. We show that for $n_e \lesssim 10^{-9}$ cm^{-3} the same mechanism would cause excessive spectral distortion of the cosmic microwave background (CMB). This small-n_e parameter region had been left open by the most restrictive previous constraints based on the dispersion of quasar (QSO) spectra. The combination of CMB and QSO limits suggests that the photon-axion conversion mechanism can only play a subleading role for SN Ia dimming. A combined analysis of all the observables affected by the photon-axion oscillations would be required to give a final verdict on the viability of this model.

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I. INTRODUCTION

Supernovae of type Ia (SNe Ia) at redshifts $0.3 \lesssim z \lesssim 1.7$ appear fainter than expected from the luminosity-redshift relation in a decelerating Universe [1, 2, 3]. On the other hand, the cosmic microwave background (CMB) anisotropy and large-scale structure observations suggest that the Universe is spatially flat, with a matter density of approximately 30% of the critical density [4, 5]. The "concordance model" thus implies that the Universe must be accelerating today because it is dominated by a "dark energy" component (about 70% of the critical density) with an equation of state $w = p/\rho \approx -1$.

The lack of a satisfactory fundamental explanation for this component has triggered wide-ranging theoretical investigations of more or less exotic scenarios [6]. Some years ago Csáki, Kaloper and Terning [7] (CKT I) suggested that the observed achromatic dimming of distant SNe Ia may be a consequence of the mixing of photons with very light and weakly coupled axion-like particles in the intergalactic magnetic fields. Though still requiring some non-standard fluid (e.g. with $p/\rho \simeq -1/3$) to fit the flatness of the universe, this model seemed capable to explain the SN dimming through a completely different mechanism without apparently affecting other cosmological observations.

Later it was recognized that the conclusions of CKT I can be significantly modified when the effects of the intergalactic plasma on the photon-axion oscillations are taken into account [8]. Assuming an electron density $n_e \approx n_{\rm baryons} = n_\gamma \eta \sim 10^{-7}{\rm cm}^{-3}$, the model is ruled out in most of the parameter space because of either an excessive photon conversion or a chromaticity of the dimming. Only fine-tuned parameters for the statistical properties of the extragalactic magnetic fields would still allow this explanation. On the other hand, Csáki, Kaloper and Terning [9] (CKT II) criticized the assumed value of n_e as being far too large for most of the intergalactic space, invoking observational hints for a value at least one order of magnitude smaller. For $n_e \lesssim 2.5 \times 10^{-8}$ cm^{-3}, the photon-axion mixing hypothesis works even better with the plasma, because the constraints from CMB anisotropies via photon-axion conversion can be relaxed.

If distant SNe Ia are dimmed by this mechanism, the same would apply to other sources. In particular, one would expect a dispersion in the observed quasar (QSO) spectra. An analysis based on the first data release of the Sloan Digital Sky Survey excludes a large part of the parameter space [10], suggesting that only for $n_e \lesssim 10^{-10}$ cm^{-3} the axion mechanism is still able to explain a dimming by 0.1 magnitudes or more. If the QSO spectra had an intrinsic dispersion at the 5% level would rule out axion dimming exceeding ~ 0.05 mag. Future data will be sensitive to yet larger regions in parameter space, yet QSOs will never be sensitive to very low n_e.

A similar bound has been obtained by a possible violation of the reciprocity relation between the luminosity distance and the angular-diameter distance [11, 12]. However, this constraint is less robust than the QSO one because it is affected by possibly large systematic errors that are difficult to quantify [13].

The purpose of our paper is to further constrain the photon-axion conversion model by studying its effect on the CMB spectral shape. We will show that the low-n_e region of parameters left open by the QSO limit is ruled out by our new limit, leaving little if any room for the axion hypothesis to mimic cosmic acceleration.

In Sec. II we discuss the formalism of photon-axion conversion and in Sec. III we summarize its effect on SN Ia dimming. In Sec. IV we describe the constraints coming from spectral CMB distortions and in Sec. V we combine our new limits with those from QSO dispersion. Finally, in Sec. VI we draw our conclusions and comment on the viability of the photon-axion conversion mechanism.

II. PHOTON-AXION CONVERSION

Axions and photons oscillate into each other in an external magnetic field [14, 15, 16, 17] due to the interaction term

$$\mathcal{L}_{a\gamma} = -\frac{1}{4}\, g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \mathbf{E}\cdot\mathbf{B}\, a\,, \tag{1}$$

where $F_{\mu\nu}$ is the electromagnetic field tensor, $\tilde{F}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$ is its dual, a is the axion field, and $g_{a\gamma}$ is the axion-photon coupling (with dimension of inverse energy). We always use natural units with $\hbar = c = k_\mathrm{B} = 1$. For very relativistic axions, the equations of motion in the presence of an external magnetic field B reduce to the linearized form [15]

$$(\omega - i\partial_z + \mathcal{M}) \begin{pmatrix} A_x \\ A_y \\ a \end{pmatrix} = 0\,, \tag{2}$$

where z is the direction of propagation, A_x and A_y correspond to the two linear polarization states of the photon field, and ω is the photon or axion energy. The mixing matrix is

$$\mathcal{M} = \begin{pmatrix} \Delta_{xx} & \Delta_{xy} & \frac{1}{2} g_{a\gamma} B_x \\ \Delta_{yx} & \Delta_{yy} & \frac{1}{2} g_{a\gamma} B_y \\ \frac{1}{2} g_{a\gamma} B_x & \frac{1}{2} g_{a\gamma} B_y & \Delta_a \end{pmatrix}\,, \tag{3}$$

where $\Delta_a = -m_a^2/2\omega$. The component of $\mathbf{B}$ parallel to the direction of motion does not induce photon-axion mixing. The quantities Δ_{ij} with $i, j = x, y$ mix the photon polarization states. They are energy dependent and are determined both by the properties of the medium and the QED vacuum polarization effect. We ignore the latter, being sub-dominant for the problem at hand [8].

For a homogeneous magnetic field we may choose a coordinate system aligned with the field direction. The linear photon polarization state parallel to the transverse field direction $\mathbf{B}_T$ is denoted as $A_\parallel$ and the orthogonal one as $A_\perp$. Equation (2) becomes then

$$(\omega - i\partial_z + \mathcal{M}) \begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix} = 0\,, \tag{4}$$

with mixing matrix

$$\mathcal{M} = \begin{pmatrix} \Delta_\perp & \Delta_\mathrm{R} & 0 \\ \Delta_R & \Delta_\parallel & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix}\,. \tag{5}$$

Here, $\Delta_\perp = \Delta_\mathrm{pl} + \Delta_\perp^\mathrm{CM}$, $\Delta_\parallel = \Delta_\mathrm{pl} + \Delta_\parallel^\mathrm{CM}$, $\Delta_\mathrm{pl} = -\omega_\mathrm{pl}^2/2\omega$, $\Delta_{a\gamma} = g_{a\gamma}|\mathbf{B}_T|/2$, and $\omega_\mathrm{pl}^2 = 4\pi\alpha\, n_e/m_e$ defines the plasma frequency, m_e being the electron mass and α the fine-structure constant. The $\Delta_{\parallel,\perp}^\mathrm{CM}$ terms describe the Cotton-Mouton effect, i.e. the birefringence of fluids in the presence of a transverse magnetic field where $|\Delta_\parallel^\mathrm{CM} - \Delta_\perp^\mathrm{CM}| \propto B_T^2$. These terms are of little importance for the following arguments and will thus be neglected. The Faraday rotation term Δ_R, which depends on the energy and the longitudinal component B_z, couples the modes $A_\parallel$ and $A_\perp$. While Faraday rotation is important when analyzing polarized sources of photons, it plays no role for the problem at hand.

With this simplification the $A_\perp$ component decouples, and the propagation equations reduce to a 2-dimensional mixing problem with a purely transverse field $\mathbf{B} = \mathbf{B}_T$

$$(\omega - i\partial_z + \mathcal{M}_2) \begin{pmatrix} A_\parallel \\ a \end{pmatrix} = 0, \tag{6}$$

with a 2-dimensional mixing matrix

$$\mathcal{M}_2 = \begin{pmatrix} \Delta_\mathrm{pl} & \Delta_{a\gamma} \\ \Delta_{a\gamma} & \Delta_a \end{pmatrix}. \tag{7}$$

The solution follows from diagonalization through the rotation angle

$$\vartheta = \frac{1}{2}\arctan\left(\frac{2\Delta_{a\gamma}}{\Delta_\mathrm{pl} - \Delta_a}\right). \tag{8}$$

In analogy to the neutrino case [18], the probability for a photon emitted in the state $A_\parallel$ to convert into an axion after traveling a distance s is

$$\begin{aligned} P_0(\gamma \to a) &= \left|\langle A_\parallel(0)|a(s)\rangle\right|^2 \\ &= \sin^2(2\vartheta)\sin^2(\Delta_\mathrm{osc} s/2) \\ &= (\Delta_{a\gamma} s)^2 \frac{\sin^2(\Delta_\mathrm{osc} s/2)}{(\Delta_\mathrm{osc} s/2)^2}\,, \end{aligned} \tag{9}$$

where the oscillation wavenumber is given by

$$\Delta_\mathrm{osc}^2 = (\Delta_\mathrm{pl} - \Delta_a)^2 + 4\Delta_{a\gamma}^2\,. \tag{10}$$

The conversion probability is energy-independent when $2|\Delta_{a\gamma}| \gg |\Delta_\mathrm{pl} - \Delta_a|$ or whenever the oscillatory term in Eq. (9) is small, i.e. $\Delta_\mathrm{osc} s/2 \ll 1$, implying the limiting behavior $P_0 = (\Delta_{a\gamma} s)^2$.

The propagation over many random B-field domains is a truly 3-dimensional problem, because different photon polarization states play the role of $A_\parallel$ and $A_\perp$ in different domains. This is enough to guarantee that the conversion probability over many domains is an incoherent average over magnetic field configurations and photon polarization states. The probability after travelling over a distance $r \gg s$, where s is the domain size, is [19]

$$P_{\gamma\to a}(r) = \frac{1}{3}\left[1 - \exp\left(-\frac{3P_0\, r}{2s}\right)\right]\,, \tag{11}$$

with P_0 given by Eq. (9). As expected one finds that for $r/s \to \infty$ the conversion probability saturates, so that on average one third of all photons converts to axions.

III. PHOTON-AXION CONVERSION AND SUPERNOVA DIMMING

To explore the effect of photon-axion conversion on SN dimming we recast the relevant physical quantities in terms of natural parameter values. The energy of optical photons is a few eV. The strength of widespread, all-pervading B-fields in the intergalactic medium must be less than a few 10^{-9} G over coherence lengths s crudely at the Mpc scale, according to the constraint coming from the Faraday effect of distant radio sources [20]. Along a given line of sight, the number of such domains in our Hubble radius is about $N \approx H_0^{-1}/s \approx 4 \times 10^3$ for $s \sim 1$ Mpc. The mean diffuse intergalactic plasma density is bounded by $n_e \lesssim 2.7 \times 10^{-7}$ cm^{-3}, corresponding to the recent WMAP measurement of the baryon density [4]. Recent results from the CAST experiment [21] give a direct experimental bound on the axion-photon coupling of $g_{a\gamma} \lesssim 1.16 \times 10^{-10}$ GeV^{-1}, comparable to the long-standing globular-cluster limit [17]. For ultra-light axions a stringent limit from the absence of γ-rays from SN 1987A gives $g_{a\gamma} \lesssim 1 \times 10^{-11}$ GeV^{-1} [22] or even $g_{a\gamma} \lesssim 3 \times 10^{-12}$ GeV^{-1} [23]. Therefore, suitable numerical values of the mixing parameters are

$$\begin{aligned}
\frac{\Delta_{a\gamma}}{\mathrm{Mpc}^{-1}} &= 0.15\, g_{10}\, B_{\mathrm{nG}}\,, \\
\frac{\Delta_{a}}{\mathrm{Mpc}^{-1}} &= -7.7 \times 10^{28} \left(\frac{m_a}{1\,\mathrm{eV}}\right)^2 \left(\frac{\omega}{1\,\mathrm{eV}}\right)^{-1}\,, \\
\frac{\Delta_{\mathrm{pl}}}{\mathrm{Mpc}^{-1}} &= -11.1 \left(\frac{\omega}{1\,\mathrm{eV}}\right)^{-1} \left(\frac{n_e}{10^{-7}\,\mathrm{cm}^{-3}}\right)\,, \qquad (12)
\end{aligned}$$

where we have introduced $g_{10} = g_{a\gamma}/10^{-10}$ GeV^{-1} and B_{nG} is the magnetic field strength in nano-Gauss.

The mixing angle defined in Eq. (8) is too small to yield a significant conversion effect for the allowed range of axion masses because $|\Delta_a| \gg |\Delta_{a\gamma}|, |\Delta_{\mathrm{pl}}|$. Therefore, to ensure a sufficiently large mixing angle one has to require nearly massless pseudo-scalars, sometimes referred to as "arions" [24, 25]. Henceforth we will consider the pseudoscalars to be effectively massless, so that our remaining independent parameters are $g_{10}B_{\mathrm{nG}}$ and n_e. Note that m_a only enters the equations via the term $m_a^2 - \omega_{\mathrm{pl}}^2$, so that for tiny but non-vanishing values of m_a, the electron density should be interpreted as $n_{e,\mathrm{eff}} = |n_e - m_a^2 m_e/(4\pi\alpha)|$.

The distance relevant for SN Ia dimming is the luminosity distance d_L at redshift z, defined by

$$d_L^2(z) = \frac{\mathcal{L}}{4\pi\mathcal{F}}\,, \qquad (13)$$

where $\mathcal{L}$ is the absolute luminosity of the source and $\mathcal{F}$ is the energy flux arriving at Earth [1, 2]. Usually the data are expressed in terms of magnitudes

$$m = M + 5\log_{10}\left(\frac{d_L}{\mathrm{Mpc}}\right) + 25\,, \qquad (14)$$

where M is the absolute magnitude, equal to the value that m would have at $d_L = 10$ pc. After a distance r, photon-axion conversion has reduced the number of photons emitted by the source and thus the flux $\mathcal{F}$ to the fraction $P_{\gamma\to\gamma} = 1 - P_{\gamma\to a}$. Therefore, the luminosity distance becomes

$$d_L \to d_L/(P_{\gamma\to\gamma})^{1/2} \qquad (15)$$

and the brightness

$$m \to m - \frac{5}{2}\log_{10}(P_{\gamma\to\gamma})\,. \qquad (16)$$

Distant SNe Ia would eventually saturate ($P_{\gamma\to\gamma} = 2/3$), and hence they would appear $(3/2)^{1/2}$ times farther away than they really are. This corresponds to a maximum dimming of approximately 0.4 mag.

In Fig. 1 we show qualitatively the regions of n_e and $g_{10}B_{\mathrm{nG}}$ relevant for SN dimming at cosmological distances. To this end we show iso-dimming contours obtained from Eq. (16) for a photon energy 4.0 eV and a magnetic domain size $s = 1$ Mpc. For simplicity we neglect the redshift evolution of the intergalactic magnetic field B, domain size s, plasma density n_e and photon frequency ω. Our iso-dimming curves are intended to illustrate the regions where the photon-axion conversion could be relevant. In reality, the dimming should be a more complicated function since the intergalactic medium is expected to be very irregular: there could be voids of low n_e density, but there will also be high density clumps, sheets and filaments and these will typically have higher B fields as well. However, the simplifications used in this work are consistent with the ones adopted in CKT II model and do not alter our main results.

The iso-dimming contours are horizontal in the low-n_e and low-$g_{10}B_{\mathrm{nG}}$ region. They are horizontal for any $g_{10}B_{\mathrm{nG}}$ when n_e is sufficiently low. From the discussion in Sec. II we know that the single-domain probability P_0 of Eq. (9) is indeed energy independent when $|\Delta_{\mathrm{osc}}s| \ll 1$, i.e. for $|\Delta_{\mathrm{pl}}|s/2 \ll 1$ and $|\Delta_{a\gamma}|s \ll 1$. When $n_e \lesssim$ few 10^{-8} cm^{-3} and $g_{10}B_{\mathrm{nG}} \lesssim 4$, we do not expect an oscillatory behavior of the probability. This feature is nicely reproduced in our iso-dimming contours. From Fig. 1 we also deduce that a significant amount of dimming is possible only for $g_{10}B_{\mathrm{nG}} \gtrsim 4 \times 10^{-2}$.

In CKT I, where the effect of n_e was neglected, a value $m_a \sim 10^{-16}$ eV was used. In terms of our variables, this corresponds to $n_{e,\mathrm{eff}} \approx 6 \times 10^{-12}$ cm^{-3}. As noted in CKT II, when plasma effects are taken into account, any value $n_e \lesssim 2.5 \times 10^{-8}$ cm^{-3} guarantees the required achromaticity of the dimming below the 3% level between the B and V bands. The choice B_{nG} of a few and $g_{10} \approx 0.1$ in CKT I and II falls in the region where the observed SN dimming could be explained while being marginally compatible with the bounds on B and g_{10}.

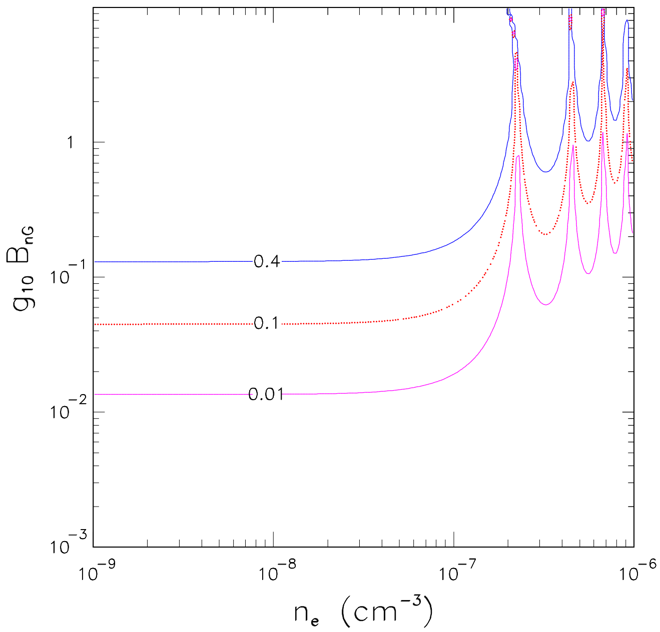

FIG. 1: Iso-dimming curves for an attenuation of 0.01, 0.1, and 0.4 magnitudes. The photon energy of 4.0 eV is representative of the B-band. The size of a magnetic domain is $s = 1$ Mpc.

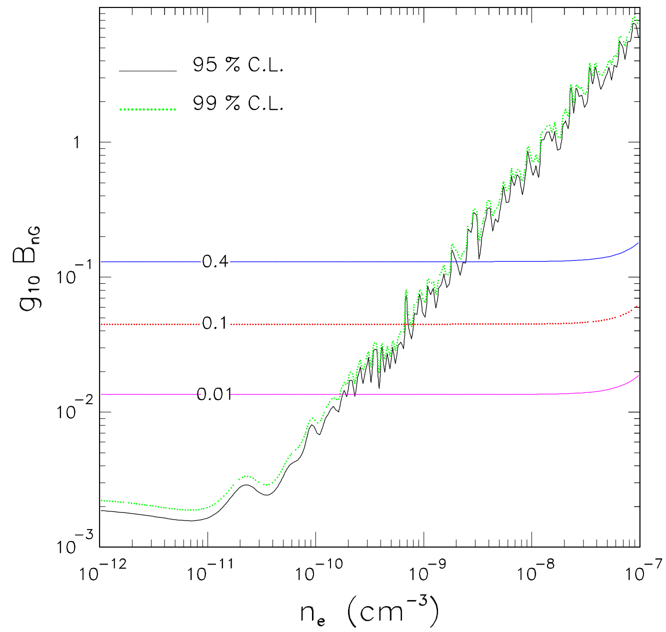

FIG. 2: Exclusion plot for axion-photon conversion based on the COBE/FIRAS CMB spectral data. The region above the solid curve is excluded at 95% C.L. whereas the one above the dotted curve is excluded at 99% C.L. The size of each magnetic domain is fixed at $s = 1$ Mpc. We also reproduce the iso-dimming contours from Fig. 1.

IV. CMB CONSTRAINTS

If $\gamma \to a$ conversion over cosmological distances is responsible for the SN Ia dimming, the same phenomenon should also leave an imprint in the CMB. We note that a similar argument was previously considered for photon→ graviton conversion [26]. Qualitatively, in the energy-dependent region of $P_{\gamma\to a}$ one expects a rather small effect due to the low energy of CMB photons ($\omega \sim 10^{-4}$ eV). However, when accounting for the incoherent integration over many domains crossed by the photon, appreciable spectral distortions may arise in view of the accuracy of the CMB data (at the level of one part in 10^4–10^5). For the same reason, in the energy-independent region, at much lower values of n_e than for the SNe Ia, the constraints on $g_{10}B_{\rm nG}$ are expected to be quite severe. The depletion of CMB photons in the patchy magnetic sky and its effect on the CMB anisotropy pattern have been previously considered in [7]. However, more stringent limits come from the distortion of the overall blackbody spectrum.

To this end we use the COBE/FIRAS data for the experimentally measured spectrum, corrected for foregrounds [27]. Note that the new calibration of FIRAS [28] is within the old errors and would not change any of our conclusions. The $N = 43$ data points $\Phi_i^{\rm exp}$ at different energies ω_i are obtained by summing the best-fit blackbody spectrum to the residuals reported in Ref. [27]. The experimental errors σ_i and the correlation indices ρ_{ij} between different energies are also available. In the presence of photon-axion conversion, the original intensity of the "theoretical blackbody" at temperature T

$$\Phi^0(\omega, T) = \frac{\omega^3}{2\pi^2}\left[\exp(\omega/T) - 1\right]^{-1} \tag{17}$$

would convert to a deformed spectrum that is given by $\Phi(\omega, T) = \Phi^0(\omega, T)P_{\gamma\to\gamma}(\omega)$. We then build the reduced chi-squared function

$$\chi^2_\nu(T, \lambda) = \frac{1}{N-1}\sum_{i,j=1}^{N} \Delta\Phi_i (\sigma^2)^{-1}_{ij} \Delta\Phi_j\,, \tag{18}$$

where

$$\Delta\Phi_i = \Phi_i^{\rm exp} - \Phi^0(\omega_i, T)P_{\gamma\to\gamma}(\omega_i, \lambda) \tag{19}$$

is the i-th residual, and

$$\sigma^2_{ij} = \rho_{ij}\sigma_i\sigma_j \tag{20}$$

is the covariance matrix. We minimize this function with respect to T [30] for each point in the parameter space $\lambda = (n_e, g_{10}B_{\rm nG})$, i.e. T is an empirical parameter determined by the χ^2_ν minimization for each λ rather than being fixed at the standard value $T_0 = 2.725 \pm 0.002$ K [28].

In Fig. 2 we show our exclusion contour in the plane of n_e and $g_{10}B_{\rm nG}$. The region above the continuous curve is the excluded region at 95% C.L., i.e. in this region the chance probability to get larger values of χ^2_ν is lower than 5%. We also show the corresponding 99% C.L. contour which is very close to the 95% contour so that another regression method and/or exclusion criterion would not change the results very much. Within a factor of a few, the same contours also hold if one varies the domain size s within a factor 10.

Comparing our exclusion plot with the iso-dimming curves of Fig. 1 we conclude that the entire region $n_e \lesssim 10^{-9}$ cm^{-3} is excluded for SN dimming.

A few comments are in order. Intergalactic magnetic fields probably are a relatively recent phenomenon in the cosmic history, arising only at redshifts of a few. As a first approximation we have then considered the photon-axion conversion as happening on present ($z = 0$) CMB photons. Since $P_{\gamma\to\gamma}$ is an increasing function of the photon energy ω, our approach leads to conservative limits. Moreover, we assumed no correlation between n_e and the intergalactic magnetic field strength. It is however physically expected that the fields are positively correlated with the plasma density so that relatively high values of $g_{10}B_{\rm nG}$ should be more likely when n_e is larger. Our constraints in the region of $n_e \gtrsim 10^{-10}$ cm^{-3} are thus probably tighter than what naively appears.

V. QSO CONSTRAINTS

Our limits are nicely complementary to the ones obtained from the effects of photon-axion conversion on quasar colors and spectra [10]. In Fig. 3 we superimpose our CMB exclusion contours with the schematic region excluded by quasars [31]. The region to the right of the dot-dashed line is excluded by requiring achromaticity of SN Ia dimming [9]. The region inside the dashed lines is excluded by the dispersion in QSO spectra. Moreover, assuming an intrinsic dispersion of 5% in these spectra, the excluded region could be enlarged up to the dotted lines. Our CMB argument excludes the region above the solid curve at 95% C.L.

A cautionary remark is in order when combining the two constraints. As we have discussed in the previous section, our CMB limits on photon-axion conversion are model independent. Conversely, the limits placed by the QSO spectra are possibly subjected to loop holes, since they are based on a full correlation between the intergalactic electron density and the magnetic field strength, which is reasonable but not well established observationally.

VI. CONCLUSIONS

We have examined the conversion of CMB photons into very low-mass axions in the presence of intergalactic magnetic fields. The resulting CMB spectral deformation excludes a previously allowed parameter region corresponding to very low densities of the intergalactic medium. Our new limits are complementary to the ones derived from

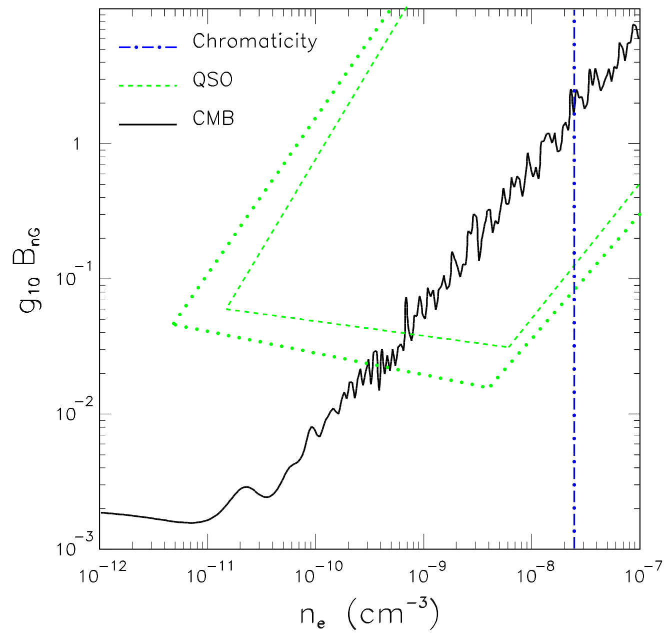

FIG. 3: Exclusion plot for photon-axion conversion. The region to the right of the dot-dashed line is excluded by requiring achromaticity of SN Ia dimming. The region inside the dashed lines is excluded by the dispersion in QSO spectra. Assuming an intrinsic dispersion of 5% in QSO spectra, the excluded region could be extended up to the dotted curve. Our CMB argument excludes the entire region above the continuous curve at 95% C.L.

QSO dispersion which place serious constraints on the axion-photon conversion mechanism. As a result, it appears that this mechanism can hardly play a leading role for the apparent SN Ia dimming.

The axion-photon conversion hypothesis has also been advocated to explain trans-GZK cutoff events in Ultra High Energy Cosmic Rays (UHECRs) [29]. In principle, UHECR photons, produced in cosmological sources far away, could drastically reduce energy losses while propagating in the intergalactic medium as axions. Some of these particles would eventually convert back to photons within a few GZK radii, thus justifying the observations of extremely high energy events as well as their isotropy. While one can not rule out the possibility that some UHE "photon-like" events at energies $E \gtrsim 4 \times 10^{19}$ eV might be due to this mechanism, our bounds imply that it can play only a subdominant role. Moreover, photons anyway are disfavored as candidates for the majority of the UHECRs.

In summary, the CMB constraints together with previous limits suggest that the fascinating mechanism of photon-axion conversion in the intergalactic magnetic fields does not play an important role for either the phenomenon of SN Ia dimming or for UHECR propagation. A definitive verdict would probably require a common analysis of SN Ia dimming, QSO spectra, and the Faraday effect of distant radio sources, based on mutually consistent assumptions about the intergalactic matter density and its distribution, the intergalactic B-field strength and its distribution and correlation with the electron density, and the redshift evolution of these quantities. Our results show that the low-n_e escape route from the QSO limits is definitely closed.

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[30] In principle, one should marginalize also over the galactic foreground spectrum [27]. However, we neglect it since it is a subleading effect with respect to the deformation induced on the CMB blackbody by the photon-axion conversion.

[31] We use the exclusion regions of astro-ph/0410501v1. In the published version [10], corresponding to astro-ph/0410501v2, the iso-dimming curves were erroneously changed. The difference is that in version 1 the angle α in Eq. (3) of Ref. [10] that characterizes the random magnetic field direction was correctly taken in the interval 0–360° whereas in version 2 it was taken in the interval 0–90° (private communication by the authors).